

# Rocket Science Unlocking Secrets of Cuvier's Beaked Whale

## Research Suggests Animals May Filter Mid-Frequency Active Sonar Sounds

**ONCE EVERY TWO** years, the Society for Marine Mammalogy presents the "Excellence in Science Communication Award" to the science professional who best demonstrates creative and effective communication techniques. The recipient of this award must present exciting, cutting edge scientific ideas to a group of peers, who deem the work worthy of top honors.

In October 2009, at the 18th Biennial Conference on the Biology of Marine Mammals, the winner of that award was Dr. Ted Cranford, a marine biologist at San Diego State University. His award-winning work was sponsored by the Office of Naval Research (ONR) and the Chief of Naval Operations Environmental Readiness Division (N45).

Cranford's winning presentation, "Knocking on the Inner Ear in Cuvier's Beaked Whale," examined the physiological effects of sound, including Navy sonar, on the hearing anatomy of Cuvier's beaked whale (*Ziphius cavirostris*). Though his findings are still undergoing validation experiments and peer-review, the preliminary research is already gaining widespread attention within the scientific community. (Note: Cranford's paper on the function and operation of the tympanoperiotic complex (TPC) in Cuvier's beaked whales has been submitted to Public Library of Science (<http://www.plos.org>). Another paper about the internal hearing structures of Cuvier's beaked whale is being drafted for submission to Hearing Research. Validation experiments are ongoing.)

"We published the first set of results just over a year ago in the *Journal of Biomimetics*," said Cranford. "A lot of unexpected results

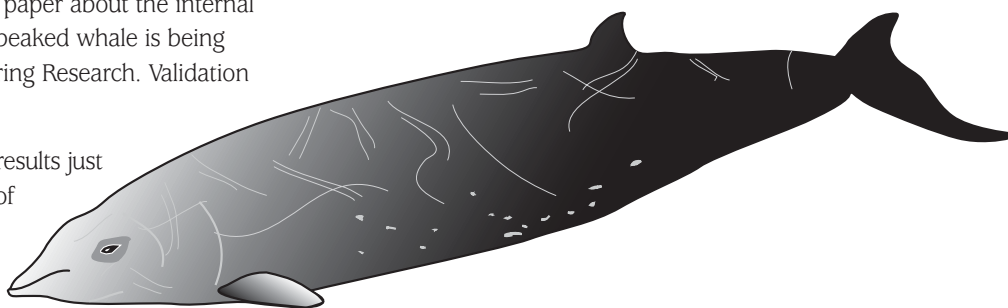
came from this paper. It gave us a brand new perspective on how these animals are able to receive sound."

"The paper's publisher—the Institute of Physics—said the paper was in the top ten percent of papers downloaded across all of the sixty or seventy journals they published in 2008. That speaks to the fact that people recognize this research is cutting edge. It's a new frontier we're embarking on," he continued. (To read the paper, visit [http://www.spermwhale.org/SDSU/My%20Work/Cranford\\_et\\_al\\_Sound\\_Paths\\_FEM\\_BB\\_2008.pdf](http://www.spermwhale.org/SDSU/My%20Work/Cranford_et_al_Sound_Paths_FEM_BB_2008.pdf).)

While the research has only recently started gaining recognition, Cranford's work studying beaked whale hearing began years ago with the discovery of a stranded beaked whale in 2002. What happened after the stranding may have unlocked a new understanding of these mysterious creatures, through use of cutting-edge technology, innovative computing techniques, and a little rocket science.

### A Mystery of a Whale

On 13 March 2002, an adult male Cuvier's beaked whale stranded alive at Gearhart Beach, Oregon, about two hours northwest of Portland. The stranding of any Cuvier's



beaked whale is a sad but fairly uncommon occurrence.

Beaked whales are among the most unusual mammals on earth. Their foraging dives are deeper than any other air-breathing animal on record, sometimes as far as 1,900 meters below the ocean's surface. The length of time they spend underwater between breaths is also unmatched—up to 85 minutes per dive. When they do eventually surface for air, they typically spend only a few minutes at the ocean's surface. This deep diving behavior makes them exceedingly difficult to find and study at sea. In fact, Cuvier's beaked whales are so rarely seen that virtually all scientific information about them comes from studying a small number of stranded specimens.

Scientists have hypothesized that beaked whales—particularly Cuvier's beaked whales—may be especially sensitive to certain sound frequencies. Based on limited research and

## Beaked Whales & Navy Sonar

**ACTIVE SONAR HAS** been identified as a contributing factor in a handful of marine mammal strandings over the past 15 years. Beaked whale strandings near Greece in 1996, the Bahamas and Spain in 2000, the Canary Islands in 2002 and Spain in 2006 have been linked to active sonar use, along with other factors. Conditions including unusual (steep and complex) underwater geography and limited egress routes (constricted channels) are believed to have contributed to these stranding events. By contrast, thousands of marine mammals die each year as a result of accidental fishing bycatch and strandings due to natural causes. (Note: For additional information on marine mammal strandings and bycatch, visit <http://www.nmfs.noaa.gov/strandings.htm> and <http://www.nmfs.noaa.gov/bycatch.htm> on the National Oceanographic and Atmospheric Administration Fisheries web page.) Concerned about the potential impact of sonar on marine species, by the year 2000 the Navy had begun funding substantial research and developing new policies and procedures to protect marine mammals.

some real-world cases where these whales have come ashore, scientists believe sound frequencies similar to mid-frequency active sonar may cause these animals to swim away from the sound source under certain conditions. (Note: Cuvier's beaked whales also swam away from killer whale (orca) sounds and random

sound samples in similar experiments. For additional details, see [http://www.navy.mil/Search/display.asp?story\\_id=44857](http://www.navy.mil/Search/display.asp?story_id=44857).)

Beaked whales are so difficult to study in the wild that determining the effects of Navy sonar on these animals is an ongoing challenge.

## The Navy's Marine Mammal Research Program

**THE NAVY HAS** done more to fund marine mammal research than any other organization in the world over the last five years, dedicating more than \$20 million in 2009 alone for marine mammal research projects.

To conduct this research, the Navy funds some of the most respected universities, research institutions, and private companies. Navy-funded marine mammal research covers many areas, including:

- Determining the distribution and abundance of protected marine species and their habitats.

- Improving understanding of effects of sound on marine mammals.
- Developing improved marine mammal protection measures to lessen such effects.
- Improving passive acoustic monitoring techniques to detect and localize marine species, particularly on Navy undersea ranges.

For more about the Navy's work in marine mammal research, see our story entitled "Navy Leads the Way in Marine Mammal Science: Continuing Investments Will Aid Decision Making, Protect Ocean Life" in the



winter 2009 issue of *Currents*. You can browse the *Currents* archive and find a digital version of the magazine at [www.enviro-navair.navy.mil/currents](http://www.enviro-navair.navy.mil/currents).

The Navy's marine mammal research program is designed to help in this process. As part of this program, the Navy conducts behavioral response studies in which researchers tag marine mammals and track their movements before, during, and after Navy sonar training exercises or simulated sonar exposures. (See our sidebars for more information on the Navy's behavioral response studies and marine mammal research program.)

mine how sound interacts with the anatomy of the animal. And Dr. Ted Cranford knew how to do just that.

"We started with the premise that we could determine if mid-frequency sonar could cause injury to beaked whales," said Cranford. "One way to determine this potential for injury and damage is through computer simulation, something called Finite Element Modeling (FEM)."

"So how do you build one of these computer models? The first thing you

## Construction Cardboard & Rocket Science

X-ray CT is a technology often used to create detailed images of internal structures in the human body. Patients are placed in a large enclosure and scanned, yielding accurate three-dimensional images which physicians can use for medical diagnoses.

"At the time, nobody had tried to scan larger animals because you couldn't get them in a hospital scanner," said Cranford. Which is why, while

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But, as the name suggests, behavioral response studies only investigate how an animal's behavior is altered as a reaction to sound. To fully understand the effects of Navy sonar on beaked whales, it is equally important to deter-

have to find is what I call the anatomic geometry. In other words, where are the structures in each head and what are their functions? The primary technology for finding this is x-ray computed tomography (CT)."

working in a Navy laboratory, Cranford was intrigued to find industrial sized CT scanners used to detect flaws in solid fuel rocket motors.

"When I found that out I thought, 'I wonder if we can use these to scan a

## Navy Behavioral Response Studies

IN 2009, MARINE mammals were monitored before, during and after naval exercises using sonar on the Atlantic Undersea Test and Evaluation Center in the Northern Bahamas and the Southern California Offshore Range in California. The Navy also collected data during biological and behavioral studies of marine mammals in the western Mediterranean Sea.

These studies involved the monitoring and tracking of marine mammals using acoustic devices and satellite tags. Several species of marine mammals were tagged during these efforts, including Blainville's beaked whales and Cuvier's beaked whales.

As a result of the studies, specialized information obtained regarding the baseline behavior of beaked whales and their response to sound will be integrated into ongoing Navy environmental planning for exercises and also be made available to science organizations worldwide to support their research efforts.

For more information on Navy-funded behavioral response studies, see our spotlight interview with Dave Moretti, Principal Investigator for the Navy's Marine Mammal Monitoring on Navy Ranges program in the winter 2010 issue of *Currents*.



The industrial x-ray CT scanner at Hill Air Force Base, UT is normally used to scan solid fuel rocket motors. Here, it prepares to scan the frozen head of a Cuvier's beaked whale enclosed in a cardboard tube.

whale head.' It took me about a year to figure out how to really do it."

In 1997, Cranford successfully scanned and mapped the three dimensional anatomy of a sperm whale's head using an X-ray CT rocket scanner at Naval Air Weapons Station in China Lake, CA.

The hardest part was determining the ideal type of container to hold the massive head, according to Cranford. The container had to rotate while keeping the head in the same condition for several days during the scanning process.

Cranford eventually settled upon using giant cardboard tubes—the same type used to pour concrete columns for freeways. The frozen whale head was placed inside the tube, and the tube was filled with insulation foam. Like a giant ice cube wrapped in a thermal blanket, the head could stay frozen for weeks. The x-rays from the scanner could easily penetrate tube and bone and create detailed images of the whale head.

Cranford employed this same process with the Cuvier's beaked whale head from Gerhardt Beach. As part of a study funded by ONR and N45, he set out to gather data on how beaked whales hear specific sound frequencies. (For more information on ONR and N45, see our sidebar.)

A colleague of Cranford's was the first to arrive at the site of the stranding on Gearhart Beach after spotting the 17-foot animal while driving by in his car.



By the time he made it down to the surf, it was too late to save the whale.

While a marine mammal stranding event is not uncommon, finding a specimen in such pristine condition is an unusual scientific opportunity for a marine biologist. And such a find was at the very top of Cranford's list.

"We are unraveling the physiology of sound production and hearing in beaked whales, which is something we don't know much about because we have so few specimens to study," said

Cranford. "The type we more frequently see is when they're dead on the beach, after a few weeks of floating in the water, which makes the carcass unusable. Getting this fresh specimen was incredibly valuable."

Cranford's colleague packed the head in ice almost immediately after discovery to preserve it. He then sent the head to San Diego, where it was placed into a giant cardboard tube along with four density rods. Density rods are narrow tubes constructed of materials with known density (such as

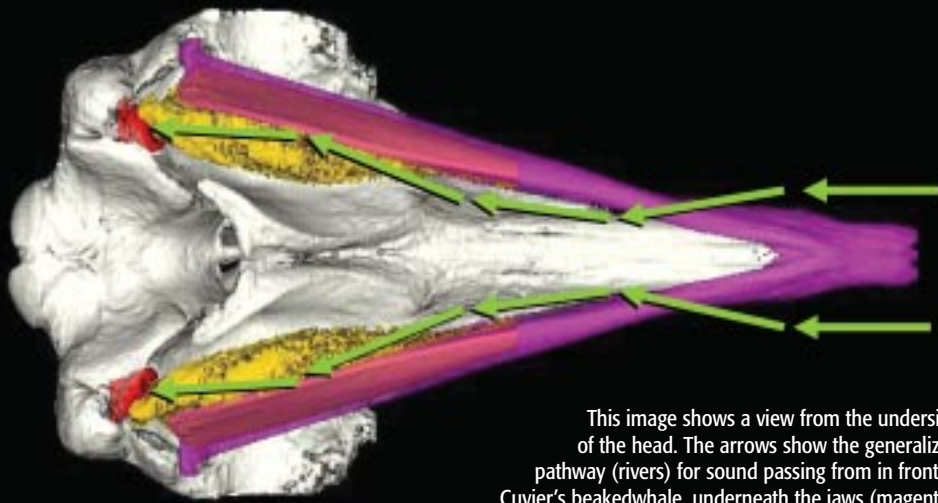
## ONR & N45

ONR AND N45 committed \$20 million for research on marine mammals and the effects of underwater sound in 2009.

ONR provides the science and technology necessary to maintain the Navy and Marine Corps' technological advantage. Through its affiliates, ONR is a leader in science and technology with engagement in 50 states, 70 countries, 1,035 institutions of higher learning and 914 industry partners.

N45 works with the fleets, systems commands and government regulatory agencies to develop effective environmental policy and ensure Sailors and Marines can train and operate in compliance with environmental laws.

For more information on ONR, visit <http://www.onr.navy.mil>. For more information on N45 and the Navy's environmental programs, visit <https://www.navy.mil/oceans>.



This image shows a view from the underside of the head. The arrows show the generalized pathway (rivers) for sound passing from in front of Cuvier's beaked whale, underneath the jaws (magenta), through the fat body (yellow), and to the ears (red).

glass or aluminum), and are used to aid researchers in analyzing the density of tissues in a CT scan.

The tube was then filled with insulating foam to preserve the specimen, and sent to Hill Air Force Base in northern Utah where the head was scanned over several days in one of the world's largest industrial x-ray CT scanners.

The scanning process revealed how the head of Cuvier's beaked whale is structured. By segmenting the CT images based on tissue density, researchers differentiated the tissues in the head for future analysis. The head was then thawed and dissected, and the elasticity of each mass was measured by Dr. Robert Shadwick at the University of British Columbia. These values, combined with the tissue density values given by the CT scan, were the two primary building

blocks for the computer model. And they took Cranford one step closer to unraveling the mystery of sound and Cuvier's beaked whale.

### Rivers of Sound

The scientific community often looks at computer modeling with skepticism. Models typically try to predict things that cannot be completely pinned down—things like the weather or the behavior of animals. But Cranford was interested in a Finite Element Model (FEM) to reveal how Cuvier's beaked whales hear.

"FEMs allow us to calculate solutions to mathematical equations that are firmly grounded in physics," said Cranford.

"It's the same reason very effective models can be built to test how a building will withstand an earthquake. The properties of the

building—steel, concrete and drywall—are all known entities."

Cranford partnered with Petr Krysl of the University of California at San Diego to develop the FEM.

"Petr is a structural engineer who knows how to build these models," said Cranford. "It's the perfect collaboration. He builds these tools and gets a lot of enjoyment out of seeing somebody use them. I get to ask all of these interesting questions, but I couldn't come anywhere near building the tools to answer them. We're making a lot of headway very quickly."

It was previously thought that beaked whales received sound through their thin lower jawbone. But the computer simulations indicated a different scenario.

Sounds arriving from in front of the animal's head actually entered through the space underneath the jaw and tongue region, through what is known as the "gular pathway." The sound passes through the throat and then through an opening in the posterior part of the hollow lower jaw, propagating along a fat body to the ear.

The model showed that the fat body, tissue and bone were all connected to channel this "river of sound" through the whale's head. The anatomy acts

Cuvier's beaked whale.  
Greg Schorr, Cascadia Research



as a wave guide to direct sound back to the animal's ears.

All living toothed whales are missing the bony wall inside the lower jaw. This feature, it turns out, is essential for this sound reception pathway to function. Some of the earliest fossils of toothed whales also show the same hollow jaw, suggesting that this pathway developed early in the evolution of whales.

"So we are not only finding out new things about this animal, but the principles we're discovering may be more broadly applicable to all living toothed whales as well as ancient whales," said Cranford.

## Hearing Sonar

To truly determine the physiological response of a beaked whale to Navy sonar, one must get to the heart of the matter. Or in this case, the inner ear.

Using existing anatomic information from a digital library, the computer model allowed Cranford to predict how the bony ear complex (tympanoperiotic complex (TPC)) would vibrate when exposed to incoming sound. This "vibrational analysis" describes how the features of the inner ear interact to produce the collective motion of the TPC.

The vibrational analysis tested sounds from 2.5 to 60 kilohertz (kHz) to determine the distribution of the sound pressure over the ear bone surface and the frequencies at which the bony ear complex vibrates.

Most U.S. Navy mid-frequency active sonar operates between 3 and 5 kHz. It turns out that those frequencies reach the ears with reduced amplitude and are largely filtered out.

Conversely, the frequencies at which beaked whales use biosonar to communicate and catch prey (12.5 kHz to 42.5 kHz) are amplified.

"This evidence suggests that Cuvier's beaked whale hearing anatomy treats sounds of different frequencies in different ways," said Cranford. "It's filtering out some sounds and amplifying others."

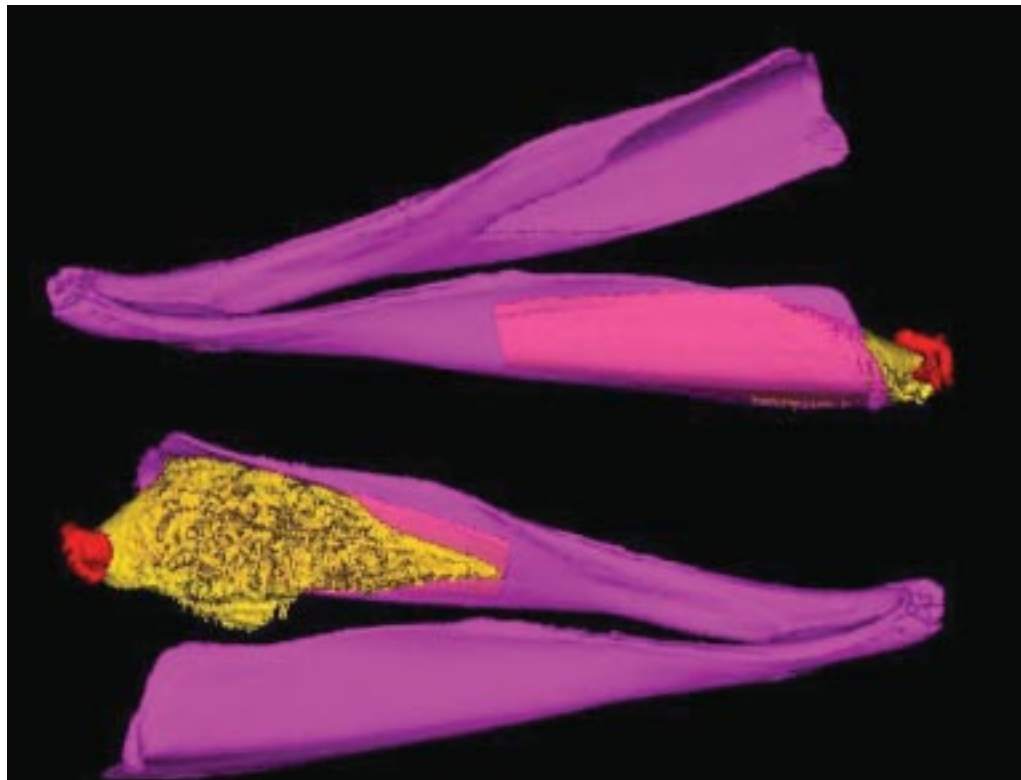
According to Cranford, one of the most powerful things about this modeling approach is that it gives researchers the ability to do virtual experiments—that is, the ability to test what would happen inside an animal's head without using a live animal. Another aspect of virtual experiments which has yet to be

tested but has enormous potential is the ability to test mitigation strategies.

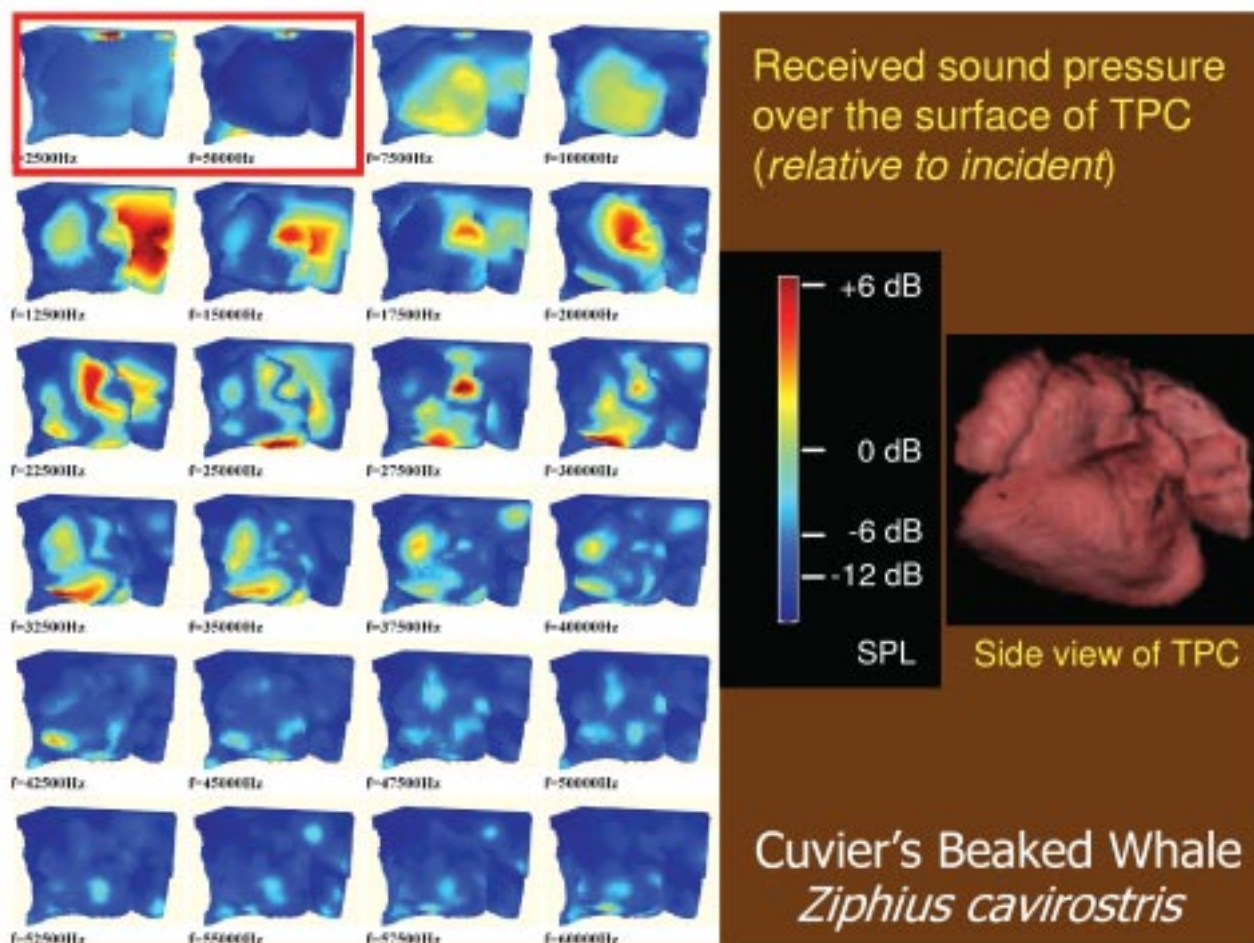
"We don't know exactly what an animal will do behaviorally when it hears a particular sound of a particular loudness or a particular frequency," said Cranford. "But these models will help us understand how a sound is going to interact with the anatomy of the animal."

These answers will also bring us closer to answering longstanding questions about the effects of Navy sonar on beaked whales.

"We are gaining a better understanding about the physics of whale hearing," said Cranford. "With this approach, we can begin to sort out which ideas have validity and which don't."



These views of the jaws (magenta) from a Cuvier's beaked whale are reconstructed from x-ray CT scans. The image on the top shows that the rear portion of the jaws is hollow and there is no bony wall on the inside. This is even more evident in the image on the bottom, as the fat body (yellow) is clearly seen because the bony wall is missing. The ear complex (red) is also shown.



The inner ear of Cuvier's beaked whale, seen in each of the 24 subpanels, was exposed to sound at various frequencies.

Researchers were able to visualize how sound was interpreted at each frequency using the key on the right.

Green means pressure is equal to the sound pressure incident on the head (0 decibels (dB)).

Blue means sound pressure is -12 dB below incident pressure, or four times less than the incident.

Red means sound pressure is +6 dB, or twice the incident pressure.

The first two subpanels (outlined in red) are the frequencies produced by Navy mid-frequency active sonar. The blue color indicates that these frequencies are largely filtered out before reaching the ear.

Ted Cranford

## Looking Ahead

"Even though these findings are promising, our next step is to reproduce the study with a similar species for which hearing tests are available, such as the bottlenose dolphin," said Cranford.

These validation experiments are currently underway. Luckily, a large amount of data already exists about the bioacoustics and biosonar of bottlenose dolphins. If Cranford applies a similar FEM approach to

bottlenose dolphins and obtains like results, this will validate his beaked whale hearing model.

"Thus far we're pointing in the right direction," said Cranford.

Cranford plans on publishing more results, especially with beaked whales found on Navy ranges. Eventually, he sees expanding the technology to other creatures of the sea.

"Each set of organisms presents its own challenges. The whales are

probably the most difficult. But they're not the only ones. The Navy is interested in what's happening to all the organisms in the ocean. And they're the only ones that are stepping up to the plate to try and figure out what the effects of sound are," he concluded. [📍](#)

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